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An Investigation into the Relevancy of the Wave shape Parameters used for Lightning Impulse Tests

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Index Terms-- Lightning Impulse, Parameters, Evaluation Methods, Breakdown behaviour, Oscillation, Overshoot, Generating Circuit, Analysing Software, Measuring Systems, Test Cells

I. Introduction

Tests with impulses are designed to demonstrate the response of high voltage equipment to transients over a wide frequency range. Lightning impulse voltages represent transients occurring in high voltage systems under operating conditions. At present the standard lightning impulse voltage is defined in IEC 60-1[1] by its peak value (U_p) and time parameters the front time T_1, the time to half value T_2.

It appeared during recent round-robin inter-comparisons that the rules for the evaluation of parameters that characterise lightning impulse voltages, like the ones given in IEC 60-1, are ambiguous, especially for front chopped impulses or when the lightning impulse has some overshoot or oscillation. It is well known that even bigger problems with the evaluation of parameters arise when the lightning impulse is a non-standard lightning impulse voltage.

For many years people have attempted to find a solution for the evaluation problems, which has been mainly focused to the definition of the mean curve, but up to now no satisfactory solution has been found. Besides the fact that the present rules for the evaluation of parameters are ambiguous, it can be questioned whether the present parameters are the most suitable ones for modern insulating materials. Also since the change from analogue to digital measuring equipment removed limitations in the number and type of parameters used to characterise lightning impulses, it seemed appropriate to start the present investigation by evaluating the relevancy of present or new parameters.

KEMA, FFII-LCOE, Schering Institute (University of Hannover) and NGC have collaborated in a project funded by the European Community. The aim of this international project is to define one or more sets of parameters to characterise lightning impulses, prove the relevancy of these parameters, establish unambiguous algorithms to evaluate them and write a proposal for the relevant parts of IEC 60-1 and IEC 1083-2. It must be emphasised that according to the authors the relevancy of parameters characterising lightning impulse voltages can be proven by performing breakdown tests. Perhaps other alternative tests are partial discharge measurements.

The project is subdivided into several phases (preparation phase, test phase, evaluation phase, result phase and service phase) it was started at 1 January 1997 and it will probably end at 1 July 1999. At the moment the project is in the test phase.

In the preparation phase literature concerning the breakdown behaviour was investigated. A questionnaire was sent to several laboratories world-wide, to obtain information about the present evaluation problems and their evaluation methods used. In the test phase the influence of overshoots, oscillations and change in front time on the breakdown behaviour of several insulating materials (SF_6, oil, XLPE and air) will be investigated.

In this paper some new information which has been acquired about the relevancy of parameters and about the evaluation methods presently used will described. It also describes how the breakdown test will be performed and which generating circuit, test cells, measuring systems and evaluation software will be used for the tests. At the end of the paper preliminary experimental results will be presented and some early conclusions will be drawn.

II. Practice and problems of Today

There has been much discussion since the introduction of digital recorders about the calculation of lighting impulse parameters, as described in IEC 60-1 and IEEE Std 4. In the past oscillograms were analysed manually by experienced engineers using pencil, ruler and judgement. Now computers are used to establish the parameters using mathematical tools; the 'analogue' algorithms for establishing parameters, according to IEC 60-1, are translated into 'digital' algorithms.

Deleted:

[1] KEMA Nederland B.V. High-Voltage Laboratory, [2] Fundacion para el Fomento de la Innovacion Industrial-LCOE, [3] Schering Institute (university of Hannover), [4] NGC Engineering & Technology.

Reproducibility of the calculation of the parameters with various algorithms is possible for smooth impulses, but the definitions in IEC 60 and IEEE Std 4 are insufficient for the evaluation of wave shapes with oscillations and/or overshoot.

Hereafter, first a brief revision of the definitions of IEC 60-1 relating to full and chopped lighting impulses is given, in order to point out where the problems of interpretation are. Later the results of the questionnaire are given.

A. Definitions of IEC 60-1

1) Definitions applicable for lighting impulses (full or chopped).

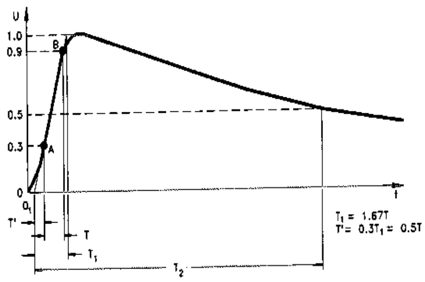


Figure 1: Evaluation rules for a Full lightning impulse according to IEC 60-1

Value of the test voltage

For a lighting impulse without oscillations, the value of the test voltage is its peak value.

With some test circuits, oscillations or overshoot may occur at the peak of the impulse, see Figure 2 a) to d); if the frequency of such oscillations is not less than 0,5 MHz or the duration of overshoot not more than 1 µs, a mean curve should be drawn as in Figure 2 a) and b) and, for the purpose of measurement, the maximum amplitude of this curve is chosen as the peak value defining the value of the test voltage.

Overshoot or oscillations in the neighbourhood of the peak, measured by a system according to IEC Publication 60-2, are tolerated provided their single peak amplitude is not larger than 5% of the peak value.

For other impulse shapes (see for example Figure 3 e)-h) the relevant Technical Committee shall define the value of the test voltage taking into account the type of the test and test object.

Front Time T_1

The front time T_1 of a lighting impulse is a virtual parameter defined as 1,67 times the interval T between the instants when the impulse is 30% and 90% of the peak value Up, (points A and B, Figure 1).

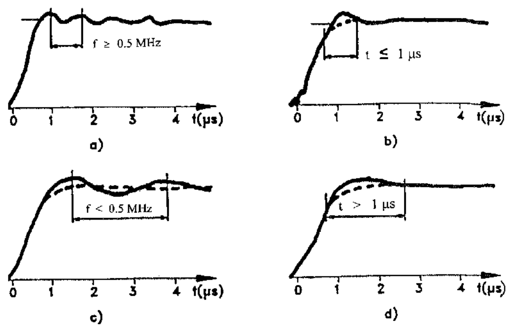


Figure 2: Evaluation rules for lightning impulses with overshoot or oscillation

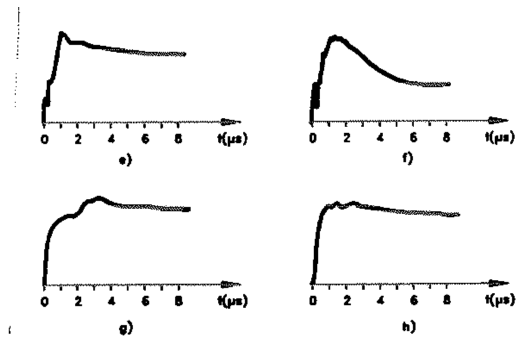


Figure 3: Examples of non standard lighting impulses

Virtual Origin O_1.

The virtual origin O_1 of a lighting impulse is the instant preceding that corresponding to point A (see Figure 1) by a time 0,3 T_1. For records having linear time scales, this is the intersection with the time axis of a straight line drawn through the reference points A and B on the front.

Time to half-value T_2.

The time to half-value T_2 of a lighting impulse is a virtual parameter defined as the time interval between the virtual origin O_1 and the instant when the voltage has decreased to half the peak value.

2) Definitions applicable only to chopped impulses

Instant of chopping

The instant of chopping is that at which the rapid collapse of voltage which characterises the chopping first occurs.

Time to chopping T_c.

The time to chopping T_c is a virtual parameter defined as the time interval between the virtual origin O_1 and the instant of chopping.

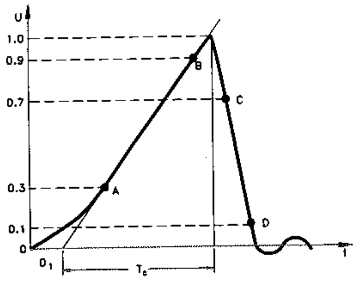


Figure 4: Evaluation rules for a lightning impulse chopped on the front

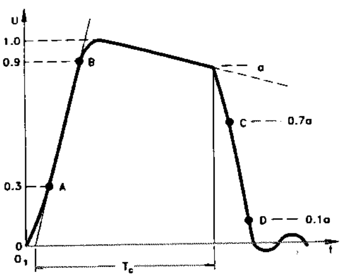


Figure 5: Evaluation rules for a lightning impulse chopped on the tail

3) Tolerances

If not otherwise specified by the relevant Technical Committee, the following differences are accepted by IEC 60-1 between specified values for the standard impulse and those actually recorded:

- Peak value: ± 3%
- Front time: ± 30%
- Time to half-value: ± 20%

Note: Even if it is not clearly explained in IEC 60-1 it should be understood that the peak voltage is the peak voltage of a mean curve in cases as Figure 2 a) and b) of the standard, in order to check the tolerance of ± 3%.

B. Problems with the interpretation of the standard.

Hereafter some of the problems associated with the definitions and interpretation of the standard are listed:

- What is the criteria to calculate the reference mean curve, specially for impulses that have overshoot and oscillations superimposed at the same time?
- How to determine the instants when the impulse is 30% and 90% of the peak value when there are oscillations superimposed on the front and/or at the peak. For instance, how to determine these two instants when there is more than one crossing point between the recorded impulse and the 30%Up and 90%Up horizontal lines?
- In order to calculate the front time, T_1 when there are oscillations superimposed at the peak which is the peak value that should be used as reference of the 100% of the impulse, the peak value of the impulse or the peak value of the mean curve?
  Note: According to the standard the peak value of the impulse should be used, but this subject is a source of many different interpretations.
- How should the frequency and amplitude of the oscillations superimposed be calculated, and with which accuracy in order to apply one evaluation criterion or the other to determine the test voltage?
- How should the overshoot amplitude and its duration be calculated in order to compare them with the 5%Up and 1,0 μs values?
- What is the physical background that supports the "magical 0,5 MHz value" for the frequency of oscillations and the "1 μs value" for the duration of the overshoot?
- How should non standard wave shapes be evaluated? For instance in case oscillations or overshoot of amplitude >5%Up are present, which is very usual in transformer testing, see Figure 6.

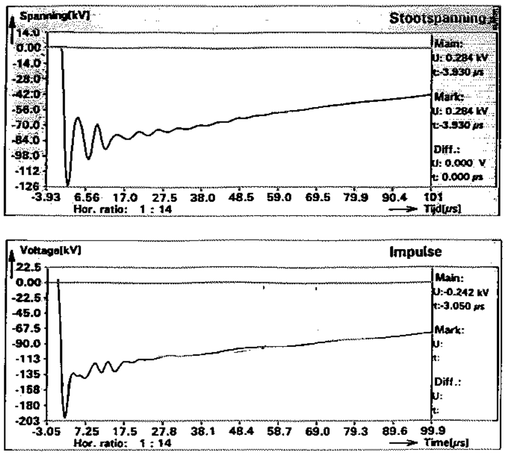


Figure 6: Typical lightning impulses in transformer testing

- Are the parameters described in IEC 60-1 really the parameters which characterise the breakdown process, or are there other parameters that could describe these processes better?
- Do all the parameters that describe the behaviour of one dielectric medium (air), describe also the behaviour of others (XLPE, SF6, oil, vacuum,...)?

Certainly these are not all the open questions to solve, but probably they cover most of the problems associated with dielectric testing.

C. Information supplied by laboratories involved in dielectric testing.

In order to know how the high-voltage laboratories around the world are facing the problems when evaluating lighting impulses and which evaluation methods are used, two different questionnaires (one for manufacturers and testing laboratories and another one for calibration laboratories) were prepared.

The questionnaire for manufacturer and testing laboratories had three sections and the one for calibration laboratories only two. In the first section questions are asked about the kind of internal insulation for different products that the laboratories are testing or manufacturing and about the kind of measuring instrumentation used to measure voltage and time parameters of lighting impulses. In this section also questions are asked about details of the test circuit that they think are of relevance in case oscillations and overshoot are present.

The second section deals with how these laboratories evaluate voltage and time parameters in case of full and chopped impulses with oscillations superimposed ($f \geq 0.5$ MHz) and/or overshoot ($d \leq \mu s$).

In the third section of the questionnaire, applicable only for manufacturers and testing laboratories, questions are asked about the possible influence on the breakdown behavior of dielectric materials of these overshoots and/or high frequency oscillations with small amplitude superimposed to the lighting impulse.

D. Results of the questionnaires.

The questionnaires were answered by 23 manufacturer laboratories, by 8 testing laboratories, and by 12 calibration laboratories, all over the world.

The manufacturers laboratories were classified in power transformers, cables and other high voltage equipment manufacturers.

Some of the questions were focused on the evaluation of lightning impulses when high frequency oscillations ($f \geq 0{,}5$ MHz) or short duration overshoot ($d \leq \mu s$) are superimposed to the impulse. The main conclusions are summarized below.

Conclusions for manufacturer laboratories.

For full impulses:

- The majority of manufacturers of power transformers and cables use the maximum value as the test voltage while the majority of manufacturers of other high voltage equipment considers peak value of the mean curve.
  In case of manufacturers of power transformers and cables, the overshoot and oscillations superimposed are provoked by the test object and in case of manufacturers of other high voltage apparatus the overshoot and oscillations superimposed are usually due to the generator and measuring system, and not due to the test object, and probably that is why power transformer and cables manufacturers don't usually follow the evaluation criteria of IEC 60-1.
- Only some manufacturers of transformers use mean curve (determining the 30% and the 90% of peak value level measured in the original wave shape with oscillations) to determine time parameters.
  The majority of the laboratories uses a mean curve (determining the 30% and the 90% of peak value of the mean curve) to determine time parameters.

For chopped impulses the conclusions are the subsequent:

- In general, the manufacturers of cables do not respond, probably because the test of chopped impulses are not conducted in cables.
- Between the two methods to determine the test voltage (maximum value, or the peak value of the mean curve) the majority uses the maximum value. About 30% of the manufacturer laboratories supplied information of the possible influence on the breakdown behaviour of different dielectric materials, when overshoot and/or high frequency oscillations are superimposed to the lightning impulse.

The result of the answers is that there is no agreement at all. This situation shows the need of the present project, since there is not a sufficient background on this matter.

Conclusions for testing laboratories

For full impulses:

- All laboratories consider the peak value of the mean curve as the test voltage, which is in accordance to the standard IEC 60-1.
- The majority of the laboratories uses a mean curve that removes the oscillations to determine the time parameters.

For chopped impulses:

- Almost all laboratories consider the maximum value at the test voltage.
- The majority of the laboratories considers the time when the voltage decreases suddenly as time to chopping.

The answers for testing laboratories are in a better agreement between them than the ones of manufacturer laboratories, and are also in better agreement with IEC 60-1.

Conclusions for calibration laboratories

For full impulses:

- The half of the laboratories considers the peak value of the mean curve as the test voltage and the other considers the maximum value as the test voltage.
- The majority of the laboratories uses a mean curve that removes oscillations to determine the time parameters.

Calibration laboratories propose also some following alternative methods for evaluating lightning impulses:

Method1. Comparison of the wave shapes of the reference measuring system and the approved measuring system being calibrated.

Method2. Use of a tolerance band. The tolerance band is determined taking into account the uncertainty of the reference measuring system.

For chopped impulses:

- The majority of the laboratories considers maximum value as the test voltage.
- There is not agreement in how to determine the time to chopping, although in the major part of the answers the time to chopping is considered by the time when the voltage decreases suddenly.

E. Confirmation of the need of the research

The main conclusion of the questionnaires is that different laboratories are using different algorithms and evaluations methods, (quite far of the IEC 60.1 rules in some cases, as for power transformers manufacturers), and so that the differences in the obtained parameters are large.

On the other hand there is not a well established physical background about the relevancy of the different parameters, and the information supplied by the laboratories on this subject is contradictory.

III. LITERATURE INVESTIGATION

In order to identify the relevant parameters for the characterisation of lightning impulse voltages, it is necessary to have knowledge about the physics of the breakdown and about the outcome of experiments which have already been performed in this area. Before carrying out any testing a literature review was made to evaluate the influence of parameters (such as oscillations, overshoot and front time) on the breakdown behaviour of XLPE, Oil, SF_6, Air and Vacuum. Little information was found on such systems that exist in practical equipment. A brief summary is set out below for XLPE, Oil, SF_6 and Air

F. XLPE

The breakdown behaviour of cross-linked polyethylene (XLPE) depends of course on the one hand on the cross-linking method, the quality of the material and the age, shape and dimensions of the test specimen and on the other hand on the test arrangements concerning to the temperature, the external test conditions, the duration and method of pre-stress and the shape, frequency and duration of the stress voltage.

Investigations on the breakdown behaviour of XLPE-cables under lightning impulse voltage stresses (1.2/50) and oscillation impulses[2] have shown, that the impulse strength is higher by using lightning impulses with negative polarity. Also the strength increases about 30% if only unipolar impulses were used instead of bipolar ones. Furthermore it was carried out that for short impulses and voltages with a high frequency the breakdown voltage also increases.

Some of these results correspond with the findings of investigations on the treeing inception of XLPE-samples in a needle-plane arrangement under standard lightning impulse voltage stresses[3]. These investigations showed that there is a strong dependence of the tree inception voltage on the polarity of the needle whereas time between the pulses and the pulse shape shows only a small influence. It has been proven that a variation of the front time from 0,6 µs to 2,3 µs and of the time to half value from 6 µs to 95 µs has a small or nearly no influence.

Also investigations on the impulse strength of different polyethylene materials were carried out resulting in the fact, that there is no significant difference in the impulse strength between XLPE, PE and PE containing voltage-stabilisers[4]. All materials possess a nominal value of the mean breakdown strength at room temperature of at least 100 kV/mm, which decreases up to 15-30% for rising temperatures.

Concluding these investigations it becomes obvious, that the polarity and the peak voltage are decisive parameters concerning the breakdown behaviour of polyethylene materials under lightning impulse voltage stress, whereas the time parameters as front and half-value time show only a small influence. For oscillating impulses the frequency of the oscillation is important for the breakdown characteristic but that does not indicate, if this could be applicable for lightning impulse voltages superimposed by oscillation in the front, peak or tail. To prove if there is an effect is part of our investigations.

G. Oil

The breakdown behaviour differs fundamentally from that of gases and solids[5]. It is critically governed by impurities, by the ageing condition as well as by space charges. As a consequence of this there is no unified breakdown theory, even though certain mechanisms are beyond doubt. Besides depending on the impurities, the electric strength also depends upon several other parameters, particularly upon pressure and the stress duration. During impulse voltage stressing the breakdown of a configuration is many times the value for alternating voltages. The impulse voltage-time curve of an electrode configuration in transformer oil reproduced in Figure 7 gives and idea of the effect of stress duration.

Figure 7: Impulse voltage time band of the rod rod electrode configuration in oil for negative impulse voltage

Some literature[6], reports results about tests performed with oscillatory and steep fronted impulses. It appeared that the breakdown behavior of oil depends on the frequency and damping oscillation. The 50% breakdown voltage of mineral oil impregnated pressboard gaps for cosenoidal waves of frequency between 0.2 MHz and 1.15 MHz is higher than U50% for lightning impulses.

In addition for cosenidal waves if the frequency increases the U50% decreases, and the U50% increases if the cosenoidal wave is more damped.

From the literature investigations it became obvious that the polarity and the wave shape are important parameters. What the influence is of oscillations and overshoot when they are superimposed on a standard lightning impulse, was not easy to deduct from the literature and will therefor be part of our investigation.

H. SF_6

The breakdown behaviour of SF_6 depends, as it is valid for all gasses, on the configuration of the electrodes, the polarity of the applied impulse, the pressure and the gas composition.

For SF_6 systems, it is recognised that the breakdown voltage in the case of steep front impulses (rise time of 50 ns) is lower than that for a standard lightning impulse voltage. This is valid for both positive and negative polarities. This implies that the front time or the dv/dt is a parameter that is of strategic importance [7]. In the context of the present study, there is evidence in the literature that the presence of oscillations superimposed on the lightning impulse wave, can influence the discharge mechanism in pressured SF_6, resulting in a significant change in the insulation breakdown voltage of the system.

The following concepts are applicable for gas dielectric media (SF_6 and air), where the discharge process is associated with current impulses which have two characteristics parts (according to first Maxwell equation):

$$i(t) = i_1(t) + i_2(t)$$

$i_1(t)$: Predischarge current impulse, injected into the electrode, caused by moving charges.

$i_2(t)$: Displacement current, caused by the high frequency oscillating voltage and the rise of the capacitance between streamer head and the other electrode.

$$i(t) = \int_A \vec{S} \cdot d\vec{A} + \frac{\partial}{\partial t} \int_A \vec{D} \cdot d\vec{A}$$

$$i(t) = \frac{q \cdot \vec{V} \cdot \vec{E}}{u} + C \cdot \frac{\partial u}{\partial t} + u \cdot \frac{\partial C}{\partial t}$$

When there are oscillations of relevant amplitude (>40% of the peak voltage) superimposed to lighting impulses, the discharge mechanism depends on the frequency of the oscillations and the pressure of the gas. For instance for 1 bar the discharge process depends mainly on $i_1(t)$ below 1 MHz, and depends mainly on $i_2(t)$ above 8 MHz. For other gas pressures the transition can be seen in the next figure.

Uosc: breakdown voltage for lightning impulses with oscillations superimposed evaluated as the peak value.

$U_{1.2/50}$: breakdown voltage for smooth lightning impulses.

For 1 bar and oscillation frequencies in the kHz range up to 1 MHz all investigations have shown higher breakdown levels compared to smooth lightning impulses. The reason is the interrupted leader propagation during the negative cycle of the oscillation. With rising frequency there is a reduction of the insulation breakdown voltage, for instance for 1 bar the breakdown level of the 10 MHz oscillation is lower than the breakdown level with smooth impulses.

For more information about SF6, see references /[8]/, /[9]/, /[10]/, /[11]/, /[12]/, /[13]/, /[14]/, /[15]/, /[16]/ and /[17]/.

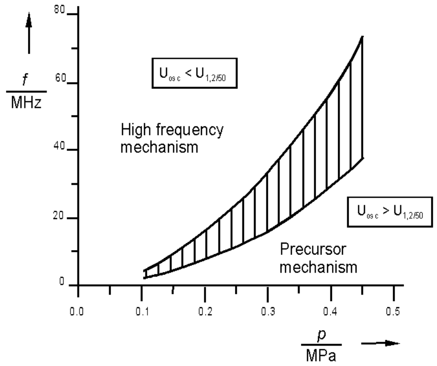


Figure 8: Influence of frequency on breakdown voltage for SF6

I. Air

The breakdown behaviour of air depends, as it is valid for all gasses, on the configuration of the electrodes, the polarity of the applied impulse, the pressure and the gas composition. Humidity, dust and charge carriers play an important role in the composition of the gas.

Some relevant information was found in the literature, for air at atmosphere pressure. For the case of a switching impulse, which has oscillations of amplitude ß ≥ 3%, it appeared that if the frequency of the oscillation is varied between 20 kHz and 200 kHz, the $U_{50\%}$ for the impulse with superimposed oscillations is higher than that for the impulse without superimposed oscillations. This implies that the absolute peak value, which should be taken in this case according to IEC 60-1, is not the most relevant parameter.

In the case of standard impulses, experimental information is, in general, sufficient to estimate the dielectric strength of the configurations of practical interest.

In the case of non standard impulses, suitable models have to be evolved to predict the behaviour of the insulation.

Various approaches have been proposed to evaluate the strength under non standard overvoltages. The approaches may be grouped into three main categories namely,

- Physical approaches, which, in their general form, evaluate the time to breakdown, T_s, for a given applied voltage, as the sum of the times necessary for the development of the various phenomena involved in the discharge (time to corona inception T_1, time necessary for streamers propagation, T_s, time necessary for leader propagation, T_1).
- Integration methods (e.g. constant area criteria) which consider the time integral of the difference between the applied voltage and a fixed voltage (in some cases this difference is raised to a power, n, different from unity). Breakdown is assumed to take place when the integral reaches a fixed value, depending on configuration and voltage polarity. According to this approach the disruptive effect is defined as:

$$DE = \int_{t_1}^{t_d} [U(t) - Ub]^n \cdot dt$$

Where if n=1, DE is the area of the impulse over the voltage level Ub, and:

- U(t): voltage wave shape of the impulse
- t_1: first time when U(t) exceeds Ub
- t_d: breakdown time

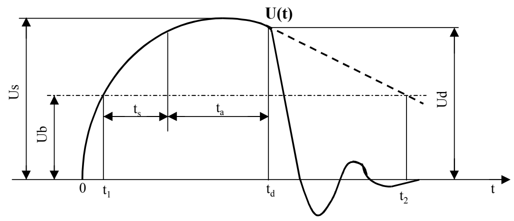


Figure 9: Disruptive effect in air

When the value of DE reaches a fixed value the breakdown takes place. If the voltage U(t) doesn't overcome the Ub value the breakdown never occurs. The value of DE is not diminished for U(t) values lower than Ub, (it means negative areas are not considered, only positive).
The value of n is not well defined and depending on the literature consulted coefficients of n=1 [19], or n=2,25 [22] can be found.
For homogeneous field Ub is the static breakdown voltage, or long duration impulse flashover voltage with switching impulses; for inhomogeneous field Ub is usually found by testing and investigation, but never differs a lot to the 50% flashover voltage for switching impulses.

- Simple formulae interpolating the various sets of data available.

For more information, consult references /[18]/, /[19]/, /[20]/, /[21]/ and /[22]/ .

IV. How to do the breakdown tests

As may have become clear from the previous paragraphs, there is not enough material available to base a selection of relevant parameters. One way to prove which parameters are relevant and which are not is to perform breakdown test with lightning impulse voltages of different wave-shapes.

One of the questions was, with which wave shapes the breakdown tests have to be performed so the outcome of the results will be internationally accepted.

Since the outcome of this project might result into a change, an addition to or a confirmation of the evaluation rules as described in present standard IEC 60-1, this IEC 60-1 should be used as a basis.

In the present standard it is said that for some wave shapes a 'mean curve' has to be drawn and it sets some limits for the front time and the time to half value. Therefor the project team decided to use for the breakdown tests lightning impulses which are variations to the standard lightning impulse as described in IEC 60-1. At first it was thought that the generation of the lightning impulse voltages of different wave-shapes could be done with one generating circuit. This however led directly to the discussion: how to establish the mean curve? Another problem of using one generating circuit is that it is nearly impossible to change for instance the overshoot or oscillation frequency without influencing the front time and time to half value, which makes the interpretation of the results very difficult.

The project team has therefor decided to use two generating circuits, one generating circuit to generate the standard lightning impulse voltages of different shapes (e.g. front times, time to half value) and one generating circuit for the generation of the oscillations and overshoot, see Chapter III.

Since breakdown tests consume a lot of time a selection had to be made between the materials to be tested and the lightning impulse voltage wave-shapes to be generated.

The project team chose for the insulating materials:

- oil (using multiple level method)
- XLPE (using multiple level method)
- air (using up and down method)
- SF_6 (using up and down method)

For the lightning impulse voltage wave shapes the following wave shapes were selected.:

Standard lightning impulses with:

- front times varying between 0,84 μs and 1,56 μs
- tail times varying between 40 μs and 60 μs
- superimposed oscillations of frequencies: 200 kHz, 500 kHz, 800 kHz, 2 MHz and 5 MHz
- superimposed overshoots of duration times: 5 μs, 2,5 μs, 1 μs and 0,625 μs.

Of course when possible or when necessary more than these wave shapes can or will be generated, but only performing the tests above mentioned will imply more than 5000 tests.

One of the problems which has to be solved right now is: when to trigger the oscillating circuit? The generating circuit chosen (consisting of two circuits which can be triggered separately) gives the freedom to choose between a lot of possibilities. Since the results of the breakdown tests performed on different insulating materials have to be compared and since the results of the breakdown tests have to be easy to analyse it is important to answer this question as accurate as possible.

One of the possibilities is to let the two peaks (of the lightning impulse and the oscillation) coincide, which result in strange curves for high frequency oscillation, see Figure 10.

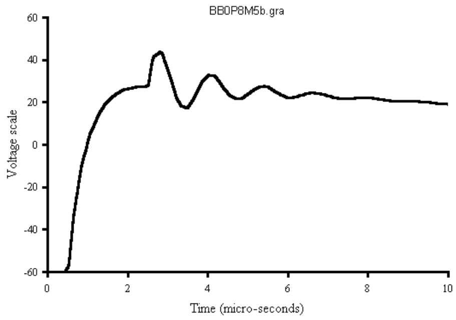


Figure 10 Example of a wave shapes of which the peakvalues coincide

Another possibility is to trigger the oscillating part at such a time, that the wave always has a smooth front, see Figure 17. The disadvantage is that the results might be difficult to analyse.

At this moment the triggering is under discussion amongst the project team and no decision have been made. Most likely some test have to be carried out before any final decision can be made. In the next chapter some more details of the problem with the triggering will be discussed.

III. GENERATING CIRCUIT

As has been mentioned in previous paragraphs, the generating circuit is composed of two independent generators, whose output voltages are applied to each electrode of the test cell where a dielectric medium is tested. In this paragraph it is explained of which components the circuits exists, it shows some results of simulations and real measurements and it explains some advantages and disadvantages.

All partners use the same basic test circuit which has two secondary circuits which are very nearly independent, one to generate the 'clean' lightning impulse (the Reference Mean Curve, RMC) and the second to generate the oscillation or overshoot to be superimposed on the RMC.

Before it was possible to start the investigations and measurements on the different materials, it was necessary to check the behaviour of the generating circuit. Also the influence of the two parts of the circuit on each other has to be inspected. Besides this, each partner had to adapt these circuits to suit the equipment available to their own laboratory. Therefore extensive simulations have been performed which proved, that the chosen generating circuit shows suitable results. Simulations software packages like Maple, PSpice or Microcap were used to simulate a generating circuit, which bases on a Marx multiplier circuit for producing the impulse voltage. The four generating circuits used, are described in Figure 11, Figure 12, Figure 13 and Figure 14. In one of the next paragraphs attention will be paid to the dimensioning of the circuit.

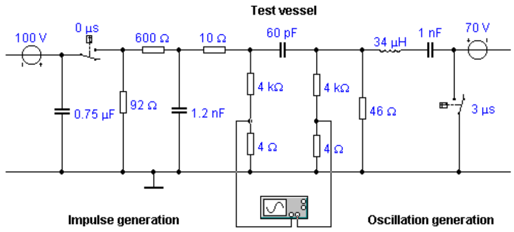


Figure 11. Generating circuit used by NGC

The left hand side of this circuit generates the standard lightning impulses and the right hand side of this circuit generates the oscillations or overshoot. The test vessel for SF_6 is in the middle.

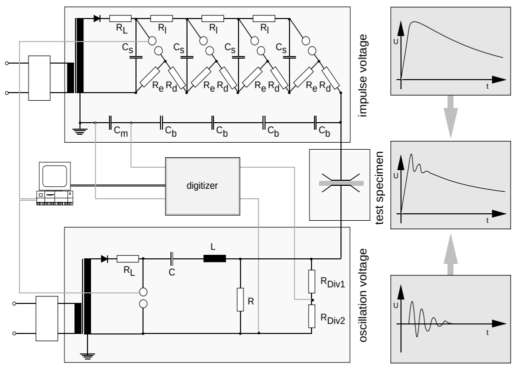


Figure 12: Generating circuit used by the Schering Institute

C_S =	6000 pF	R_L =	10 MΩ
C_b =	1200 pF	R_{Div1} =	10310 Ω
C_m =	1800 nF	R_{Div2} =	2.54 Ω
R_L =	10 MΩ	C,L,R =	variable
R_l =	50 kΩ	R_e =	9500 Ω
R_d =	400 Ω		

The upper part of the used circuit shown in Figure 12 generates a standard lightning impulse and the lower part the superimposed oscillation or overshoot at an adjustable time delay between the beginning of the lightning impulse and the superimposed voltage. The test cell for XLPE is in the middle.

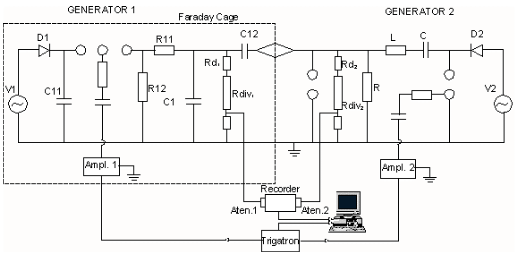


Figure 13: Generating circuit used by FFII: Generator 1 for full smooth impulses. Generator 2 for oscillation and overshoot wave shapes. Test Cell (C_{12}) between both generators

The generator 1 from Figure 13 generates full smooth impulses and the generator 2 oscillation or overshoot wave shapes. The test cell for air is in the middle. A rod or sphere gap is placed in the output of the generator 2 to avoid damages in this generator or in its measuring system when the breakdown occurs in the test cell.

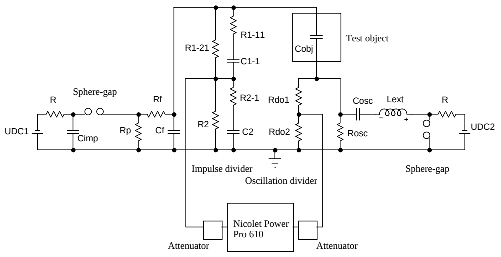


Figure 14: Generating circuit used by KEMA

The left hand side of the circuit of Figure 14 generates the smooth impulses and the right hand side of this circuit generates oscillations or overshoot. The test object (test cell for oil) is in the middle. The measuring systems are presented by their components.

A. *Dimensioning of the circuit*

As have been mentioned before, impulses of different wave shapes have to be generated. The dimensions of the components of the oscillation circuit have to be adapted to the different oscillation frequencies or overshoot duration. There are two things that have to be considered, first it is that the components have the correct values for obtained the desired wave shape and second is that the influence of the one circuit to the other circuit is small.

Generally some capacitors with certain values are available in each lab and the needed inductance has to be figured out. In order to dimension the components, simulations have to be made. For simulating the complete circuit of Figure 12, with the help of PSpice, the equivalent circuit shown in Figure 15 was used. In which the switches are emulated spark gaps.

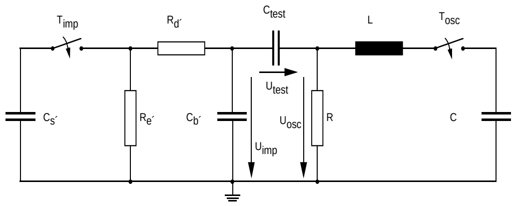


Figure 15: PSpice model of the generating circuit of the Schering Institute

$C_{S'}$ = 1500 pF C_{test} = 20 pF
$C_{b'}$ = 300 pF C,L,R = variable
$R_{e'}$ = 38 kΩ
$R_{d'}$ = 1600 Ω

For the various oscillating frequencies which should be used for the investigations on the breakdown behaviour the values of the elements of the oscillation circuit for the PSpice model as well as for the used circuit are shown in Table 1: Dimensioning of the oscillation circuit

The reason for the difference between the calculated and the used inductance values are the stray capacitance of about 50 pF and the circuit inductance of about 5 μH. The impedance is always selected that way, that the positive amplitude of the 3rd oscillation is higher than 5% of the maximum positive amplitude of the oscillating voltage and that the 4th positive amplitude is lower than 5%. To determine the correct value of this impedance it is necessary to solve the corresponding differential equation of the oscillation considering the mentioned parasitic effects like stray-capacitance or circuit inductance.

Table 1: Dimensioning of the oscillation circuit

Elements of the oscillation circuit					
Oscillation Frequency		Model parameters		Circuit parameters	
	R [Ω]	C [pF]	L [μH]	C [pF]	L [μH]
200 kHz	40	6000	105.5	6000	103.1
500 kHz	77	1200	84.4	1200	75.7
800 kHz	50	1200	32.9	1200	28.7
2000 kHz	200	100	63.3	100	34.3

The wave shapes generated for each generator can be easily derived under the hypothesis of ideal components and no influences between both generators. In consequence, for the circuits used for this project C12 must not arise more than several tens of pF because C1 is not higher than a few of nF. In addition, R must not be higher than several tens or hundred Ohms when the oscillation frequency is around 5 MHz or 0,5 MHz respectively. In addition, with these same restrictions, it is possible to assure that the most part of the high voltage generated by each generator is applied to the test cell and not to the output impedance of the opposite generator.

If these restrictions are not satisfied interference will appear between both generators and no smooth lightning impulses will be generated. The following formulas show the output voltage in each generator.

Generator 1: generation of a smooth impulse.

$$U = A_0 \cdot \left(e^{\frac{-t}{\tau_1}} - e^{\frac{-t}{\tau_2}} \right)$$

Generator 2:

generation of an oscillation.

$$U = C \cdot e^{-\alpha t} \cdot \mathrm{sen}(wt)$$

$$C = \frac{R \cdot U_o}{wL}$$

$$w = \sqrt{\frac{1}{LC} - \alpha^2}$$

$$\alpha = \frac{R}{2L}$$

generation of an overshoot:

$$U = K \cdot Sh(wt)$$

$$K = \frac{2 \cdot R \cdot U_o}{\sqrt{R - 4 \cdot \frac{L}{C}}}$$

$$w = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{L \cdot C}}$$

U_o : U_{max} of V2

B. *Simulations and results*

In Figure 16 a result of a PSpice simulation (of circuit Figure 15) for a superimposed oscillation with a frequency of 500 kHz is shown. In this case the pulse capacitor was loaded up to -130 kV and the capacitor of the oscillation circuit to +35 kV. The values of all other elements correspond to the specifications in Figure 15 and Table 1: Dimensioning of the oscillation circuit

The delay time between the two switches was set to 1.2 µs.

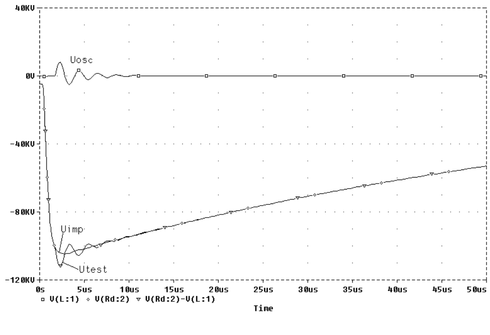


Figure 16: Diagram of a PSpice simulation

The result of the measurement corresponding to the mentioned simulation is shown in Figure 17 The values of the used elements are in agreement with the definitions in Figure 15 and Table 1: Dimensioning of the oscillation circuit

A digitizer with a sampling rate of 100 MHz and a resolution of 10 bits recorded the wave-shapes. The record length of each curve is 8192 samples. The trigger delay was set to 1.2µs.

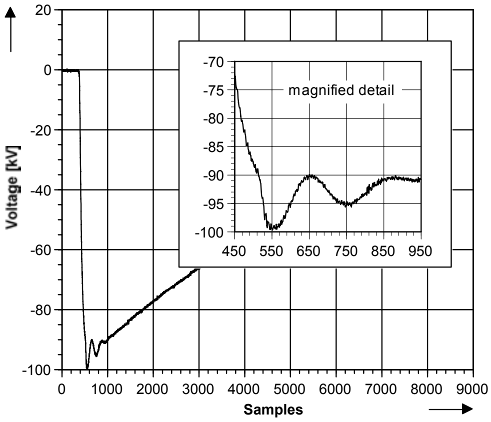


Figure 17: Measured data recorded with 100 MHz sampling frequency (1 sample = 10 ns)

From a comparison between the simulation and the measurement it becomes obvious, that there is no significant difference, thus making it possible to use this special generating circuit.

C. *advantages*

The advantages of the used generating circuit (that comprises of two circuits) are on the one hand the possibility to generate different lightning impulses superimposed by oscillations or overshoots with various amplitudes and frequencies and on the other hand the ability to measure the lightning impulse and the oscillation separately. This is the most important advantage, because for the evaluation or determination of the parameters of the wave-shape it is in some cases necessary to look especially at the mean curve.

D. *disadvantages*

However, the generating circuit used also has some disadvantages. On one side it is necessary, that the impedance of the test specimen is much higher than the impedance of the impulse and oscillation circuit, because it must be guaranteed, that the influence of the two parts to each other is as low as possible. On the other side the elements and the measuring system of the oscillation circuit have to withstand the impulse voltage, because in case of a breakdown of the specimen the high voltage generated by the impulse circuit is applied to them. Therefore it was necessary among other things to pay attention to the protection of the digitizer or the divider.

The most significant disadvantage of the circuit for oscillations of Figure 13, is its low efficiency (around 20%). A better efficiency can be obtained if the position of L is permuted by the position of R, but in this case the oscillation at generator 2 output follows a cosinosidal function with a very high steepness at the beginning of the oscillation.

E. Problems

With the generating circuits shown in the beginning of this chapter, some problems appeared:

- high frequency oscillations on the first period of the oscillations
- lope of the first period of the oscillations

When these problem occur, then consideration is required as to what is the real effective frequency. The answer to this will depend partly on the positions of the breakdowns on the applied wave, partly on the initial oscillation slope and partly on the presence f any high frequency oscillations.

Simulations have indicated that these two problems can be explained by the following:

The real circuits present non ideal components R ,L ,C.It appeared that every R, L and C had stray capacitance, internal resistance or inductance. This appeared to be of big influence to the obtained impulse shape and the oscillating shapes.

Modelling have been considered to obtain a correct simulation of the real wave shapes generated in order to solve the problems which occurred. The values of the stray capacitance, internal resistance or inductances have been obtained by doing several measurements and calculations (for example applying a low voltage step to the circuit, measuring the output with fast oscilloscope probes, measure the oscillating frequency and damping and calculation of R, L and C.)

The circuit has been studied by performing transient analysis using commercial software packages. This analysis has permitted to foresee the behaviour of each part of the circuit with a good accuracy.

In Figure 18 a complete simulation model of the generating circuit used by KEMA is given.

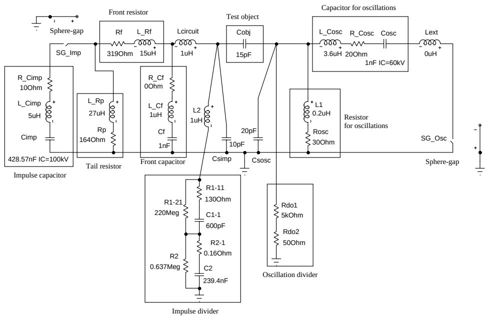


Figure 18: complete simulation model of the generating circuit used by KEMA

The problems with the high frequency oscillations and slope can be explained with an example. An example test wave is shown in Figure 19, for a 0,8 MHz oscillation.

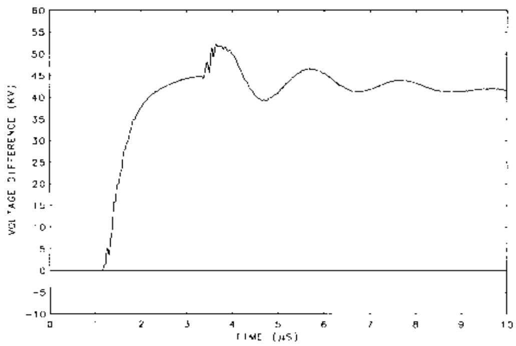


Figure 19: lightning impulse with 0,8 MHz oscillations

This illustrates the problems, firstly, the slope of the front of the oscillation is steeper than the sinusoid, and secondly, high frequency oscillations occur which have been instigated by the triggered spark gap. The initial slope can sometimes be improved in the oscillation circuit by more L, less C and greater R to maintain a given wave shape.

The amplitude of the high frequency oscillations can be reduced with capacitance across the triggered gap and by changes to components. It can be caused by incipient resonances in small circuit loops, stray inductances, and by stray capacitance from an inductor causing ‘transmission line’ resonance. It has been shown that it does not occur in the measuring system.

At the high test frequencies, 2 MHz and 5 MHz, the problems with the initial slope of the oscillation are worse; not only is the initial slope too steep but the initial peak can be less than the second peak. this problem can be overcome with a modified arrangement in which the oscillation is capacitive coupled (by the 57 pF capacitor) to the test vessel as in the circuit of Figure 20

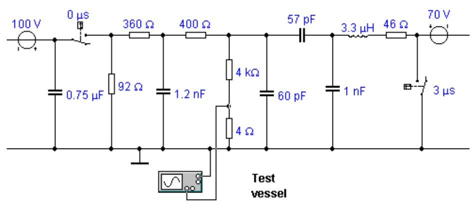


Figure 20: Test vessel capacitivly coupled to the oscillating circuit of NGC

In this case the vessel is grounded on one side and one wave shape recorded instead of two. The wave shape from the high voltage test is as shown in Figure 21 for 5 MHz.

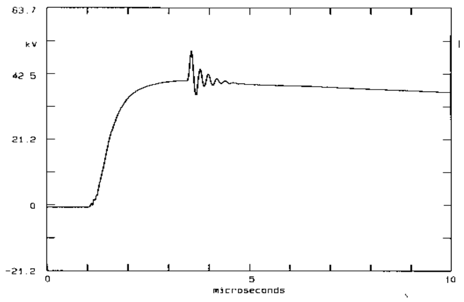


Figure 21: Lightning impulse with 5 MHz oscillations

In this case a large capacitor across the triggered gap is necessary to prevent the gap from being triggered by transfer of part of the RMC through the coupling capacitor. The effect does not arise with the original ‘back-to-back’ circuit because in that case the oscillation polarity is opposite to the RMC impulse polarity.

One other solution to this problem is to use non inductive resistors and to keep the circuit as compact as possible.

F. Triggering of both generators

As has been discussed in one of the previous chapters, the advantage of the generating circuit used is that one can choose the triggering delay between the two circuits.

There are multiple possibilities, one of the is to choose the triggering in such a way that the peak values coincide and one other option is that the triggering of each generator is synchronised to generate wave shapes as close as possible to the real dielectric tests. The Figure 22 to Figure 25 show several wave shape examples for the different frequencies of the oscillation with different delays between the two wave shapes generated. The triggering device must have a stable delay, in order to obtain comparable results for same kind wave shapes.

The problem is of course to synchronise the two parts of the whole circuit. The different partners found different solutions to this problem. One solution was the development of a special digital circuit for triggering the spark gaps by an optical signal, which was transferred via a glass fibre cable. The triggering device is also controlled by the personal computer, thus enabling this system to control the whole measurement and to perform the determination of the impulse parameters with special designed software described in one of the next paragraphs. One other solutions was to use a coupled impulse generator with a triggered chopping gap. Another solution was found in an analogue trigger delay box. The trigger delay can be adjusted to -0,03 µs to 5 µsec with a potmeter. Power MOSFETs are used for the switching of the normal triggering amplifier.

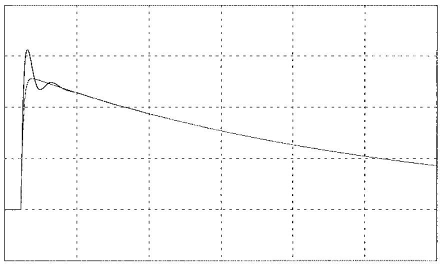


Figure 22: Lightning impulse with oscillations of frequency 0,2 MHz (15,66 kV and 13,33 µs per div)

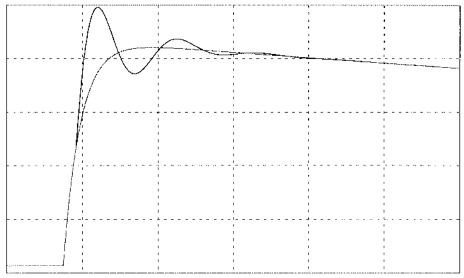


Figure 23: Lightning impulse with oscillations of frequency 0,5 MHz (9,83 kV and 1,78 µs per div)

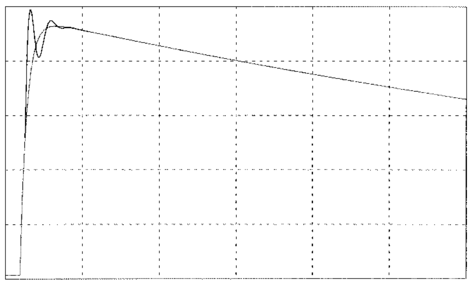


Figure 24: Lightning impulse with oscillations of frequency 0,8 MHz (8,75 kV and 4,49 µs per div)

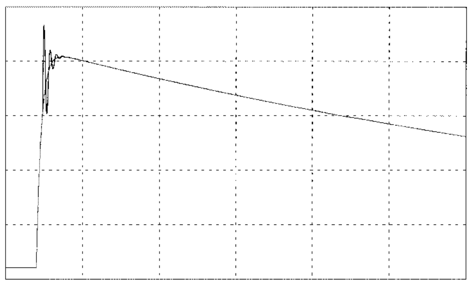


Figure 25: Lightning impulse with oscillations of frequency 2 Mhz (10,34 kV and 6,23 µs per div)

VI. different types of test cells

As has been mentioned earlier the project team selected four insulating materials to perform the breakdown test on:

- XLPE
- Oil
- SF_6
- Air

To perform the breakdown test with these materials, test cells are necessary. For each material a test cell is designed and built. The details of these test cells are given in the next paragraphs.

G. XLPE

For the investigations on polyethylene a test vessel shown in figure 5 is used.

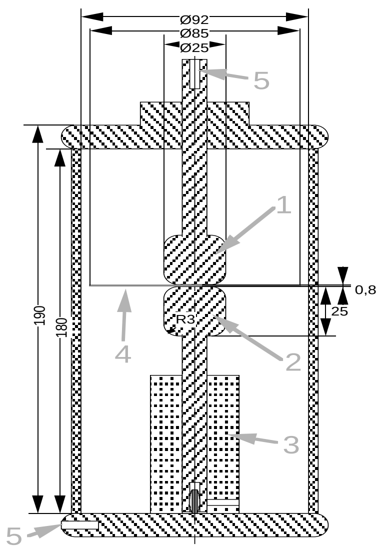


Figure 26: Test vessel for XLPE

1: moveable and replaceable brass electrode
2: replaceable brass electrode
3: holding device made of PTFE
4: HDPE specimen
5: connectors

The PMMA vessel with top and bottom covers of aluminium has two electrodes which can easily be replaced, thus making it possible to change the electrodes for new ones or to refine and to polish them after a breakdown took place. This procedure guarantees, that the test environment is always similar, thus making the results not influenced by the impurity and roughness of the surface of the electrodes as a result of a breakdown during the tests. The upper electrode of the plate-plate arrangement is, in addition to the inter-change-ability by opening the vessel respectively removing the cap, moveable in the direction of the axis.

To avoid external breakdowns and extreme surface field strengths the test set-up is floated with the transparent silicone liquid Baysilone M50EL, which has no influence on the used specimen in contrast to e. g. mineral oil which has an inflating effect on polyethylene specimens.

Since the whole test arrangement is transparent it is possible to recognise by eye whether the position of the electrodes and specimen is correct or not. Furthermore the breakdown can be recorded with a high-speed camera if necessary.

Due to the construction mentioned above the whole test vessel and the form of the electrodes are in accordance with the standard described in IEC 243[23].

As test specimen a HDPE disc with a diameter of 85 mm and a thickness of 0,8 mm is used. The probe is not especially attached but only held by the weight of the electrodes in its place. The pre-conditioning of the test specimen correspond to the standard IEC 212[24]. Some detailed information about the HDPE specimen are listed in Table 2.

Table 2: Characteristics of used polyethylene specimen

Characteristics of HDPE specimen	
Density	0.95 g/cm³
Short term operation temperature	120°C
Long term operation temperature	80°C
Dielectric permitivity (ε_r)	2.3
Dielectric dissipation factor (tan δ)	$2 \cdot 10^{-4}$
Specific resistance	10^{18} Ωm
Surface resistance	10^{13}Ω
Breakdown voltage strength	>50 kV/mm

H. Oil

For the investigations on oil a test cell as shown in Figure 27 is used. Both the upper and bottom electrode are in principle movable. During normal testing the bottom electrode will not be moved. The distance between the electrodes can be determined by means of measuring with the micrometer fixed to the upper electrode The electrodes are made of brass and they are interchangeble, for means of polishing or changing the electrode configuration from for instance sphere/sphere to point/plane or plane/sphere.

Since the breakdown behavior of oil is depending on the quality of the oil, special attention has been paid to reproducibility of the tests. The oil will be pumped into the test cell. After it has been pumped into the test cell, the air in the test cell will evacuated. This will be done for minimizing the amount of the air bubbles in the oil and the influence of the air in the vessel to the oil.

In the test vessel a system has been made for circulating the oil after every breakdown. After a certain numbers of breakdowns the oil will be replaced.

The outer tube has been made of perspex, to be able to see the oil and make high speed recordings when necessary.

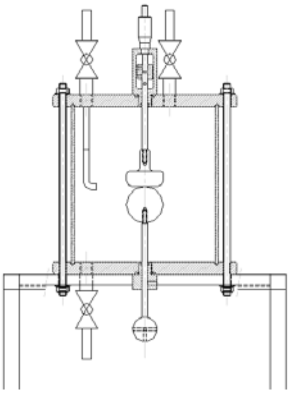


Figure 27: The test cell for oil

I. SF_6

The pressure vessel shown in Figure 28 is capable of an operating pressure up to 6 bars. The internal dimensions of the vessel chamber are: 205 mm dia x 230 mm depth. The vessel has a GRP bushing and is operated horizontally and not vertically as shown in the diagram. A hinged end plate allows access and a quartz glass window is fitted into this plate. Not shown in the figure are ports into which accessories can be fitted for special requirements including micrometer adjustments.

The stainless steel electrodes being used for the first tests have a uniform field profile with a flat diameter of 30 mm.

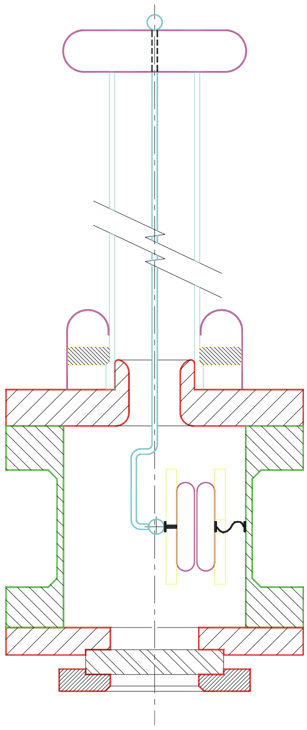


Figure 28: The SF_6 test vessel

SF_6 Gas is supplied from a portable supply/recovery plant and a fresh change of previously unused gas is used when refilling is required.

J. Air

Two different types of test cell have been prepared (see Figure 29 and Figure 30). With these cells the distance between the two electrodes is kept constant when repeating the different tests under the same conditions.

The test cells are located inside a Faraday cage with the temperature controlled within $(20 \pm 1)\,°C$. During the test, temperature, humidity and pressure are regularly measured in order to refer the results to reference conditions.

The cells are designed to have a highly uniform field in one case and non uniform field in the other.

The field efficiency factors, $\eta = E_{average}/E_{max}$ are the following:

- Test cell for uniform field: η=0.86.
- Test cell for non uniform field: η=0.02.

In the next figures the two different configurations are shown:

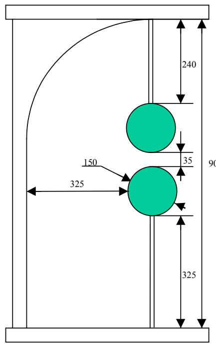


Figure 29: Test Cell for air with uniform field

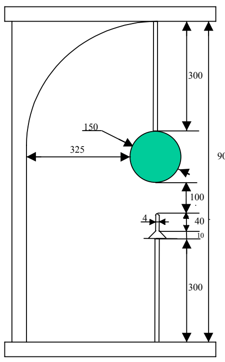


Figure 30: Test Cell for air with non uniform field

The Test Cell has been irradiated with low pressure UV-C fluorescent lamps, type TUV 15W-LL. Four lamps of 15W each were used, placed side by side in two lamp holders.

The type of UV lamps has been chosen in order to have a minimum conventional deviation, z, during the tests.

In the Figure 31 and Figure 32 the situation of the lamp holders can be seen.

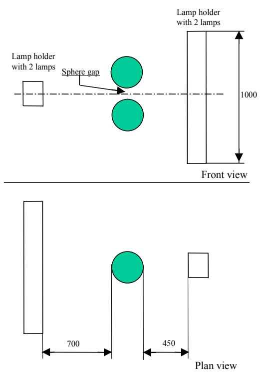


Figure 31: Position of the UV lamps for the test cell for air with uniform field

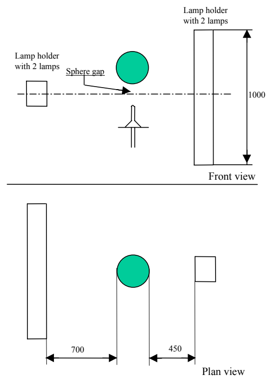


Figure 32: Position of the UV lamps for the test cell for air with non uniform field

IV. MEASURING SYSTEMS

A. Requirements for the Measuring Systems

Two measuring systems are necessary when the generating circuit described in Chapter III is used. One to measure smooth lightning impulses generated by generator 1 and the other one to measure oscillation or overshoot wave shapes generated by generator 2. Both measuring systems share the same digital recorder with two channels, one for each measuring system . The difference between the high voltage waves shapes measured by each channel is the impulse applied to the test cell.

The measuring system for smooth lightning impulses must be appropriated to measure standard lightning impulses (front times from 0,84 μs to 1,56 μs and times to half value from 40 μs to 60 μs) with a peak voltage level around 100 kV. This measuring system must have an overall uncertainty within ± 1% for the peak values and ± 5% for time parameters, as those established for a Reference Measuring System. These restrictions are not difficult to achieve because no oscillation have to be measured and the peak voltage of the impulse is maintained constant around a fixed level (100 kV). As consequence, a conventional resistive or capacitive lightning divider with a stable scale factor is appropriated for this kind of measurements.

The requirements to measure oscillation and overshoot wave shapes are however more restrictive. The scale factor must be maintained constant for oscillation frequencies from several hundred of kiloHertz to some MegaHertz and for voltage amplitudes between 5 kV and 20 kV. Since the frequency response has to be as flat as possible in this range, the dividers had to have a bandwidth of approximately 35 MHz. As there are not commercial available dividers or voltage probes for this operating range with the accuracy required, special dividers had to be built. Figure 33 and Figure 34 show two different dividers developed specially for this project.

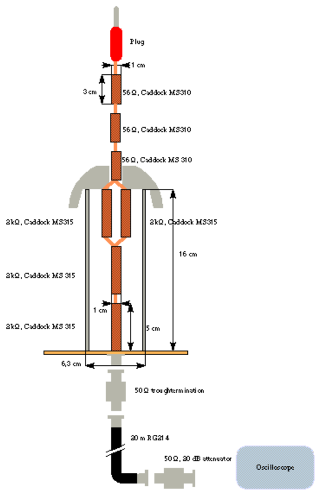
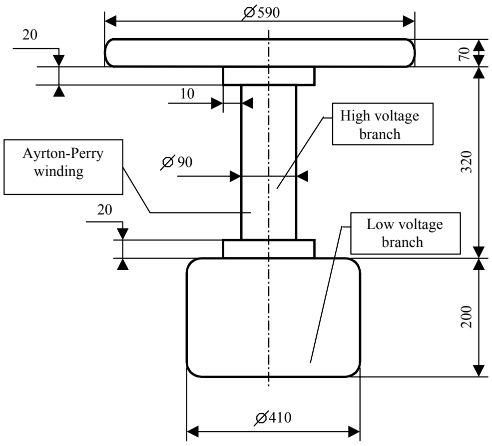


Figure 33: Divider developed by KEMA



$R_{high\ arm}$=2114 Ω

$R_{low\ arm}$=75 Ω

Figure 34: Divider developed by FFII-LCOE

B. Determination of the Scale Factor of the Measuring Systems

The method used to determine the scale factor of each measuring system, F, is by multiplying the scale factors of its components: divider with its signal transmission system, Fd, and recording instrument, Fr:

$$F = F_d \cdot F_r$$

The scale factor of the divider together with its signal transmission system, used for smooth impulses, was determined with a good accuracy (≤ 0,5%) by means of alternating voltage calibrators of up to several hundred kiloHertz (e.g: around 100 or 200 kHz) with an output voltage of around one hundred volts.

The low voltage measurements to determine the Scale Factor of the divider used for the lightning impulse together with its signal transmission system have been extended to the operation voltage (around 100 kV) by means of a linearity tests against a Reference Measuring System. Full impulses were applied to demonstrate that the linearity is better than ± 1%.

The impulse Scale Factor and the dynamic behaviour of the digitizer were determined following the specifications included in clause 2.2.6 of the IEC 61083-1 [25] and [26]by means of a pulse calibrator

However, the scale factor determination of the divider together with its signal transmission system, used to measure the oscillation and overshoot wave shapes, is more difficult because the amplitude-frequency response must be extended to several MegaHertz (oscillations of up to 5 MHz must be measured).

For this frequency range, the use of commercial alternating voltage calibrators measuring at the same time the low voltage output of the measuring system is less accurate, because the output voltage is too low, therefore can be affected by the electrical noise, and the output of the generators is at high frequencies influenced by its load (the divider). It is difficult to measure the voltage applied to the divider, so a scale factor is difficult to establish.

For this reason, the step response analysis is a good complementary way to evaluate the dynamic behavior of the divider in accordance with the requirements established in the clause 9.3.1. of the IEC 60-2 standard[27], see Figure 35. This is not an easy task, since the risetime has to be extremely short (in the range of a few nanoseconds).

At KEMA also measurements up to 100 MHz were performed with the aid of a tracking generator, see Figure 37. It appeared that the test set up had a big influence to the frequency response at surprisingly low frequencies (around 10 MHz), for example changes in the distance to other components in the range of cm or minor changes in the ground connections. It was difficult to establish if the differences were cause by the change in the output voltage of the tracking generator (input voltage to the divider) or the divider itself. Therefore the divider had to be positioned in a very constant environment.

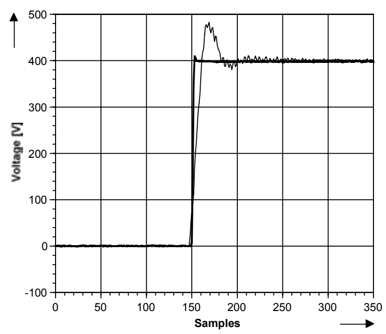


Figure 35: Step response of measuring system developed by FFII

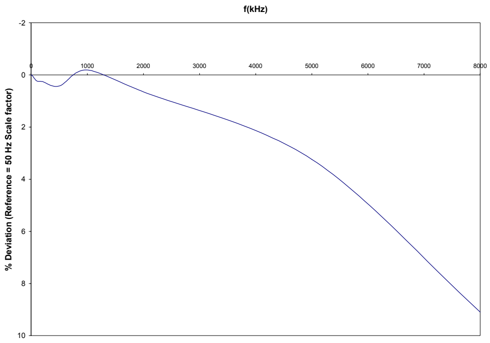


Figure 36: Amplitude-frequency response of the measuring system developed by FFII-LCOE

Figure 37: Amplitude frequency response of the divider developed by KEMA

C. Interference in the Measuring Systems

Special attention is required to avoid significant interference in both measuring systems. Each generator can provoke interference in its own measuring system or in the measuring system used for the other generator. The free distances around the dividers, a good shielding of each measuring cable and the measuring equipment and a special care with the ground connections must be taken.

V. ANALYSING SOFTWARE

As has been mentioned earlier, nowadays software is one of the tools to evaluate parameters. In this project a special written software package is used. Besides the development of this package, investigations have been performed towards new possible tools for evaluation. Both are described in this chapter.

A. Common software used in the project

The present definitions established by the IEC 60-1 for the evaluation of the lightning impulse parameters are insufficient and ambiguous. This has brought about different interpretations in the estimation of these parameters, especially using digital recorders. Therefore, clear definitions for standard parameters applicable to digitizers have been established [28] to avoid discrepancies between the partners of the project. On the basis of these definitions a software package has been developed to be used as a common tool to analyze impulses.

1) Global description of the software

The developed software includes three groups of parameters:

- Standard parameters (peak voltage, front time and time to half value or time to chopping for chopped impulses).
- Complementary parameters to calculate the basic parameters (e.g.: mean curve, frequency and amplitude of the oscillations, etc.).
- New parameters to study their correlation with the results obtained for each dielectric medium, such as: area enclosed by the recorded impulse above (or bellow for negative impulses) a certain voltage level U_L, steepness of the wave dU/dt, etc.

The first two groups of parameters are based on the traditional parameters included in the IEC 60-1 but they are complemented with new definitions. In the following paragraphs a basic description of each parameter is given.

Standard and complementary parameters

Firstly the base line (BL) is defined as the average of consecutive samples preceding the time when the impulse is applied. A number of 100 samples is considered to be enough to determine the BL, but to avoid using samples belonging to the impulse, the 10 samples before the impulse origin (O) are rejected. The O is determined as the first sample of the recorded impulse that exceeds the base level by 2% of the peak value.

The peak value (Up) is defined as the difference between the maximum absolute level after the superimposed noise is removed and the BL. In order to remove the superimposed noise on the crest of an impulse, a procedure is established for full or chopped on the tail impulses. This procedure consists in calculating the average value around the peak. Discrepancies with real peak value less than 0,5% are achieved when the noise amplitude is up to 1,5% Up for impulses that present oscillations around the peak whose frequency is not more than 2 MHz and its amplitude is not higher than 5 % of the Up. However, this method can not be applied when the sampling interval is too large in comparison with the oscillation period. In this case, the Up is calculated without removing any noise.

When oscillations appear superimposed to the impulse the reference mean curve (RMC) must be determined to calculate the frequency and the amplitudes of the oscillation. The RMC is defined as the one that minimises the root mean square of the differences with the original recorded impulse. The curve corresponding to this difference is called residual curve R(t). The oscillation frequency is determined applying the FFT or the DFT to the R(t).

In addition, it is considered that an overshoot is present in an impulse if, after removing the eventual superimposed noise and oscillations, by means the RMC, the resulting curve is above (or below for negative impulses) the single exponential function (SE) that fits the tail of the recorded impulse. The parameters associated with an overshoot are the following: the overshoot peak value (OPV), the virtual peak value (VPV), the amplitude (β) and the overshoot duration (τ). Figure 38 shows them.

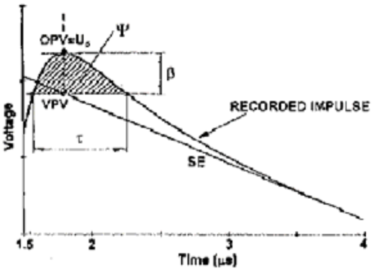


Figure 38: New definitions of the characteristic parameters of an overshoot

The software permits to calculate the front time by three different ways: Firstly, the peak voltage of the recorded impulse can be taken as the 100% level and the instants t30 and t90 are determined on the original wave. Secondly, the peak voltage of the RMC can be taken as the 100% level and the instants t30 and t90 can be determined on the basis of the RMC. Finally, a local mean curve (LMC) that fits the front of the impulse can be used to determine the instants t30 and t90 and the peak voltage of the recorded impulse is taken as the 100% level.

The Time to half value is calculated on the basis of the instant t50, which is determined by linear interpolation between the 55% and 45% of the Up on the tail of the recorded impulse.

Similarly the time to chopping for impulses chopped in the front is determined on the basis of instant of chopping t_c, which is calculated as the intersection point of the straight line through 90% and 30% of the Up in the decay voltage and the horizontal line that passes through the Up of the impulse. For impulses chopped in the tail, a similar procedure is applied, replacing the horizontal line that passes trough the Up of the impulse by the straight line that fits the tail of the impulse before the instant of chopping and calculating now the 90% and 30% of the voltage at the instant of chopping.

New parameters

The new parameters considered are based on enclosed areas by the impulse and the steepness of the impulse front. The areas to be studied as new parameters are the following:

- Area above a certain voltage level U_k (e.g.: Up of the RMC, VPV or above another specific level).
- Area of the impulse above the RMC.
- The wave du/dt for the whole recorded impulse is calculated as a tool for research.
- In addition, three control parameters to evaluate the goodness of the RMC are given: the root mean square of the residual curve, the total enclosed area by the impulse and by the RMC (these two last ones must be as close as possible).

The parameters calculated by the software have been validated. The validation was carried out using mathematical wave shapes (double exponential + damping oscillations + noise) and comparing the software results with the other ones obtained by analytical calculation.

B. Investigation towards different evaluation methods

In addition to the common software that is based on the present IEC 60-1, an investigation has been carried out towards different evaluation methods in general and an investigation has been carried out towards Genetic Algorithm based software.

1) General

For the evaluation of lightning impulses superimposed with oscillations or overshoots at the front, peak or tail the IEC 60 requires in some special cases to determine the parameters of the wave-shape with the help of a smooth mean curve, which should describe more or less a standard lightning impulse wave-shape. To determine e.g. the amount of the test voltage of a lightning impulse voltage superimposed at the peak with an oscillation higher than 0,5 MHz it is necessary to draw a mean curve, whose maximum voltage corresponds to the test voltage.

Because today most of the measurements can carried out with digital equipment[29] the measured data can be evaluated by computers with special software packages, which are able to calculate the mean curve if necessary. The digital evaluation of lightning impulses by calculating the mean curves with so called curve-fitting methods is common practice[30]. While using these methods especially the following three problems arise:

The mean curve has to be expressed by a numerical function, because only in this case a computer is able to determine it. The questions are which function is the best one or which one can describe the physical relations as good as possible.

Curve fitting bases on the concept to fit a numerical function representing the mean curve as well as possible to a measured curve. To find an ideal fitting curve is always an optimisation problem, which can be solved by different optimisation methods. The problem is which algorithm is the most useful tool to do so or which method is the most exact and unambiguous one.

All optimisation methods need a goal function, which is a mathematical equation describing the optimisation problem. That means, that in the case of using curve-fitting methods it is necessary to define a criterion that indicates how good the fitting is. The questions in this case is, which criterion is the most suitable one.

Concerning the last problem it can be noted, that almost all optimisation methods are trying to minimise a defined error function, which is in most cases described by the Least Mean Square method respectively Least Mean Square error (LMS).

The first two problems mentioned above are much more difficult to solve because they depend on each other. Many investigations were carried out to find an optimal mathematical expression of the mean curve. Aside from double exponential functions, which seem to describe standard lightning impulses well, also quadruple exponential functions, polynomial and other non-polynomial functions were investigated[31]. For each function a different number of parameters has to be determined, thus making various optimisation methods more or less useful for solving the different problems.

A special function is of course the double exponential function. This function represents the correct solution of the differential equation, which describes an equivalent impulse generating circuit as shown in Figure 15. Very often generating circuits and measurement systems are influenced by different effects, thus explaining one of the more significant deviations between a measured curve and a calculated double exponential function. It becomes obvious by regarding the starting point of the wave-shapes, that a double exponential function starts at zero straight on while the measured curve has a smooth beginning and therefore a smaller rising time Thus making it more difficult to define a zero point for the mean curve, which should replace the measured wave-shape during the evaluation process.

For this reason in this project some new functions expressing the mean curve are investigated. These functions combine exponential functions with sine and cosine functions for imitating the beginning of the curve in a more suitable way.

Due to the separately recorded wave-shapes, it is possible to test the suitability of these functions with the measured superimposed impulse voltage and afterwards to compare the results of the fitting with the measured standard lightning impulse.

As curve fitting methods also different algorithms like the Levenberg-Marquardt or the Newton-Rhapson algorithm were used and implemented in the MATLAB software package. These iterative algorithms have in general the advantage to be very fast and unambiguous if the same initialisation is used. The results generally depend on the initialisation process, thus being a disadvantage of these methods. Furthermore the efficiency of these algorithms becomes poor if the number of parameters to be determined increases, because they are not able to perform a global search in the data space.

New algorithms like neural networks, genetic algorithms or evolution strategies are predestined for a global search although they have the disadvantage, that the results depend on unpredictable effects, because they partly use random functions. Thus resulting in the effect, that different curve fittings performed on different computers or at different times will carry out different results, therefore these methods can not be classified as unambiguous.

2) Genetic Algorithm Based Software

INTRODUCTION

In addition to the core software, an investigation has been carried out to evaluate alternative equations to represent lightning impulse (LI) and switching impulse (SI). The initial stage concerns the development of an algorithm to mathematically represent mean curve of the practical LI and SI wave--shapes. Briefly, the technique is based on a Genetic Algorithm (GA) approach, which is inspired by the natural genetic selection. It has been widely used in function optimisation and control applications. Specifically, a population of individuals (potential solutions) competes with one another over successive generations, i.e. 'survival of the fittest'. After a number of generations, the best solutions survive and the less fit are gradually eliminated from the population. This enables exploitation of historical information to speculate on new solutions.

PRINCIPAL OF GENETIC SEARCHING MECHANISM

The GA based searching mechanism consists of four main functional units, (as shown in Figure 39)

- Population pools
- Selection unit
- Reproduction unit
- Evaluation unit

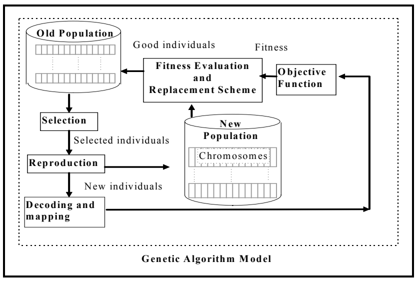


Figure 39: Block Diagram Of A GA Based Searching Mechanism

POPULATION POOL

A population pool contains a large number of individuals (chromosomes) which store the parameter values for the objective function. Random numbers initialises the individuals in the original population and the objective function and the evaluation function evaluate their fitness values. For this study, the objective function is a double exponential function, which is used to generate a smooth LI and SI. The parameters for the objective function in this study are A_1, A_2, α_1 and α_2.

$$y = A_1 e^{-\alpha_1 t} - A_2 e^{-\alpha_2 t}$$

Subsequently, the evaluation function calculates the fitness of an individual based on the differences between the given impulse and the impulse that generated by the objective function.

$$Fitness = \frac{F}{\sum \sqrt{[f(t) - O(t)]^2}}$$

where F is a multiplying factor, $f(t)$ and $O(t)$ are the given impulse and the impulse that generated by the objective function respectively.

THE SELECTION UNIT

The selection unit employs a random but biased manner to select individuals for producing new generation of individuals. In this way, fit individuals have higher probability to be selected as parents. The selection method applied in this study is the standard biased roulette wheel selection approach.

REPRODUCTION UNIT

After selecting individuals as parents, new child individuals can be reproduced by mixing and mutating the genes of the parents. The standard crossover and mutation operators have been successfully employed for this purpose.

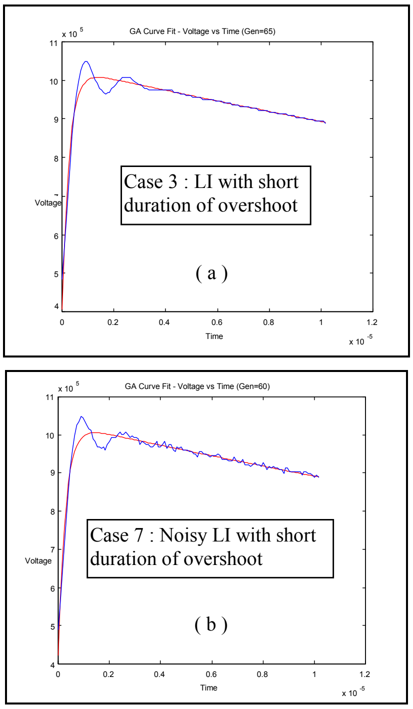


Figure 40: Examples of preliminary results produced by the GA based searching mechanism.

EVALUATION UNIT

When the reproduction process is finished, each of the individuals in the new population will be evaluated. Their fitness values are calculated by the objective and evaluation function. The iterative generation process can be stopped when the solution is converged.

VERIFICATION OF THE SOFTWARE

In order to evaluate the performance of the GA based searching mechanism, eight tests have been carried out. Some representative waves are shown at Figure 40. For each test, a LI or SI was given and the GA based searching mechanism attempted to find the appropriate coefficients for the double exponential functions which effectively represent the mean curve of the given LI or SI wave--shapes. The test data of the eight case studies were generated by the IEC-TDG, which concern smooth and noisy LI and SI with and without overshoot.

CONCLUSIONS

The preliminary results (e.g. Figure 40) show that the GA based searching mechanism is capable of finding a mean curve that closely match the given full LI or SI. As the parameter values of the double exponential function have been obtained, it is possible to derive the LI or SI parameters such as test voltage, front time etc. mathematically. Further work will be carried out shortly, which aims to improve the objective function so that the GA based technique can be used to find mathematical equations that closely represent practical LI or SI wave--shapes.

VI. PRELIMINARY RESULTS

A. *Introduction*

It can be pointed out, that in this project up to now many problems and unexpected difficulties had to be solved. After the selection of the appropriate generator and the following simulations, even until the set up of the circuits much time had been spent for the arrangement of an adequate measuring system. Due to the high used frequencies up to 5 MHz it was required to construct new dividers with an appropriate frequency response, which are capable for measuring the produced voltages.

Besides the frequency response also the step response of the dividers and the interference had been tested. Therefore the system had to be adapted until all parameters were suitable for the limits defined in the standard IEC 60.

After the preparations had now been finished, the breakdown tests could be started. Before the tests of which the results will be used for the definition of new parameters can be started, some investigations toward the stability of the system (test conditions, generating circuit, triggering delay, condition of the electrodes), reproducibility of the tests and to influencing factors were necessary. One of the things which was also agreed upon is that some tests, for instance in air will be carried out in two different laboratories.

When performing these test of course some preliminary results (since the influence of everything is not known) can be obtained. Up to now not many tests have not been carried out yet, and the following conclusions for are still provisional. But, even the first examinations for XLPE showed, that some parameters like e.g. the maximum voltage influence the breakdown behaviour of the examined specimen much more than other ones.

B. Preliminary results

For air up to now not many tests have not been carried out yet, and the following conclusions for are still provisional since they have to be checked much better.

a) Tests with smooth impulses in air.

The procedure used has been the up and down test method with 40 impulses and the test voltage is around 100 kV.

Different tests with smooth impulses have been carried out in order to analyse the influence of the impulse shape on the 50% breakdown voltage for homogeneous or inhomogeneous field configuration.

The front time (T_1), and the time to half value (T_2) have been changed inside the tolerance limits of the standard IEC 60-1, testing both test cells with five shapes of impulses: 1.56/60; 0.84/60; 1.2/50; 1.56/40 and 0.84/40.

The obtained differences in all cases are small.

For uniform field the differences of the $U_{50\%}$ values are within +0.5%,-0.9%, and for non uniform field ±0.7%.

b) Tests with impulses 1.2/50 with oscillations in air

For uniform field and oscillations superimposed on the front and at the peak:

The procedure used has been the up and down test method with 40 impulses and the test voltage is around 100 kV

- For a specific frequency of oscillations the $U_{50\%}$, measured as the peak value, increases slightly when the oscillations amplitude increases.
- The variation of $U_{50\%}$ measured as the peak value, in comparison with the $U_{50\%}$ for smooth impulses, for amplitudes of the oscillation up to $\approx$5%Up is less than 0.7%Up (for frequencies of 0,2 MHz and 0,8 MHz).

The procedure used has been the multiple level test method with 10 impulses per level and the test voltage is around 30 kV

- For oscillations with a frequency 2,5 MHz and 20% amplitude superimposed on the peak, the oscillations had 5% influence on the $U_{50\%}$ of the RMC. However the spread increased from 0,4% to 6%. A typical time to breakdown can be seen in Figure 43.

- For oscillations with a frequency 2,5 MHz and 20% amplitude superimposed on the front, the oscillations had small (<1%) influence on the $U_{50\%}$ of the RMC. A typical time to breakdown can be seen in Figure 44.

For non uniform field and oscillations superimposed on the front and at the peak:

The procedure used has been the up and down test method with 40 impulses and the test voltage is around 100 kV

- For a specific frequency of oscillations the $U_{50\%}$ measured as the peak value, increases clearly when the oscillation amplitude increases.
- For oscillations of frequencies between 0,2 MHz and 0,5 MHz up to 7% Up the $U_{50\%}$ (RMC) is closer to the $U_{50\%}$ for smooth impulses than the $U_{50\%}$ measured as the peak value. Therefore it seems not to be in accordance with the IEC 60-1.

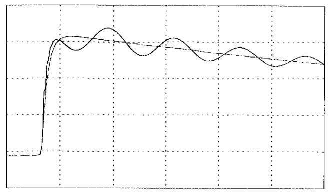


Figure 41: Impulse with oscillations of f=0,2 MHz (3,82 μs per div)

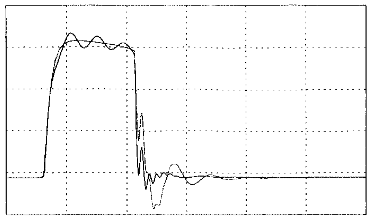


Figure 45: Impulse with oscillations of f=0,5 MHz (4,11 μs per div)

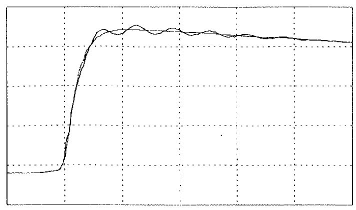


Figure 42: Impulse with oscillations of f=0,8 MHz (1,87 μs per div)

Figure 43: Breakdown in case a 2,5 MHz oscillation is superimposed on the peak (7,86 kV and 1,2μs per div)

Figure 44: Breakdown in case a 2,5 MHz oscillation is superimposed on the front peak (7,86 kV and 1,2μs per div)

VII. Conclusions

Parameters that characterise lightning impulses and methods to evaluate them are given in IEC 60-1 and IEEE Std 4. The reproducibility of the evaluation of these parameters with various algorithms is possible for smooth impulses, but the definitions in IEC 60-1 and IEEE Std4 are insufficient for the evaluation of parameters of wave shapes with oscillations or overshoot.

It can be questioned whether the present parameters are the most suitable ones to for modern insulating materials and if these are the only possible parameters to describe lightning impulses. Therefore this international project is started. The results obtained so far and the difficulties met are described in this paper. In this chapter the main conclusions are summarised.

The problems with the interpretation of the definition of the parameters are described in the beginning of this paper. These are not so easy to solve and have to be taken into account when a proposal for new definitions is made.

The main conclusion of the questionnaires is that different laboratories are using different algorithms and evaluations methods, (quite far of the IEC 60.1 rules in some cases, as for power transformers manufacturers), so that the differences in the obtained parameters are large.On the other hand there is not a well established physical backgrounds about the relevancy of the different parameters, and the information supplied by the laboratories on this subject is contradictory.

An investigation towards literature about breakdown behaviour of insulating materials provided some information, however not enough to base the introduction of new parameters or evaluation methods on.

For the investigation towards the relevancy of present and possible new parameters breakdown test are selected as a mean to prove their relevancy. Insulating materials have been selected and also wave shapes to be generated.

It appeared that the best way to generate the desired wave shapes is using two generating circuits, although this has some disadvantages. The disadvantages are however small compared to the disadvantage of only one generating circuit. Since the use of two generating circuits has the advantage that one is free to determine when to trigger the oscillating circuit, one has to answer the question if this superposition of two impulses represents the wave shapes in real test condition.This subject is under discussions right now.

In generating circuits, unwanted oscillations with high amplitude may occur caused by the non ideal components. Depending on the measuring system used, you will measure them or not. Question is how these high frequency oscillations with high amplitude influence the breakdown behaviour. Therefore a lot of effort has been put into minimising these oscillations in order to have unambigious results.

For the breakdown tests with insulating materials test cells were designed and built. These were described in detail in this paper.

Since it is the wish to carry out the measurements in this project with a high accuracy, special dividers for the measurement of the high frequency oscillations were developed. The calibration of these dividers is difficult.

For the investigation towards the relevancy of the wave shape parameters a special software package was developed. The reason of this was that all partners are using the same evaluation method. In addition an investigation was done towards new possibilities for the evaluation of parameters, using for instance Genetic Algorithms.

In the last chapter of this paper some preliminary results are given. There is some indication that some parameters other than the present parameters are also of importance and that at least for air, variations in the front and tail time in the tolerances given in IEC 60-1 do have an influence smaller than 1% to the $U_{50\%}$.

VIII. Acknowledgements

This project is partly funded by the European Commission, which is hereby thanked for doing so.

Unfortunately it was not possible to make a reference to all the papers from which information is used for this summary since the reference would be as long as this paper. The authors would however like to acknowledge all the persons who by this way contributed to our paper.

The authors would like to thank all the persons who filled in the questionnaires and all other persons who in anyway contributed to this project.

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